MET O 3 TECHNICAL NOTE 30

WIND-CHILL INDICES - THEIR HISTORY, CALCULATION AND APPLICATIONS IN THE CONSTRUCTION INDUSTRY

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1. Introduction

The term 'wind-chill' refers to the common experience that, at most temperatures, it feels colder when the wind is blowing than when it is not (Schlatter, 1981). The chilling effect of the wind for various combinations of wind speed and temperature can be quantitatively expressed by the rate of heat loss per unit area (the wind-chill index) or a wind-chill equivalent temperature.

This technical note describes the history of work undertaken to quantify the cooling effect of the wind, the formulae available for calculating wind-chill indices and equivalent temperatures and how these are of use to the building and construction industry.

Countries such as Canada and USA which regularly experience severe winter weather make use of the wind-chill concept, and weather forecasts include wind-chill equivalent temperatures, giving an indication of how cold someone will feel and the amount of clothing required to maintain a reasonable level of comfort. Such an indication may not be gleaned from a temperature forecast alone.

It is only recently that the UK Meteorological Office has issued forecasts of wind-chill equivalent temperatures to the public, though forecasts of these have been issued in the past to farmers, in connection with potentially stressful conditions for new born lambs (Starr, 1984).

2. History of Formulae used to calculate wind-chill Indices

The term 'wind-chill' was first introduced in the 1940's (Siple and Passel, 1945) to describe the wind-enhanced cooling power of the atmosphere. However, work to produce a formula to describe this cooling power predates the First World War.

The cooling of an object will be a combined function of radiation, conduction and convection (plus evaporation if the object is wet).

Following work on the cooling of hot wires, Hill produced a generalised heat balance equation for the cooling of a dry, heated body by convection and conduction to air (reference in Stone, 1943).

$$H = (a + b\, v^{0.5})\ (ts - ta)$$

where H = rate of heat loss

a = heat transfer coefficient of conduction

b = heat transfer coefficient of convection

v = wind speed

ts = surface temperature of object

ta = ambient air temperature

No term for radiation effects is included. An equilibrium between incoming and outgoing radiation was assumed but this does not happen very often in practice.

Hill calculated the constants of the equation using a katathermometer - an alcohol thermometer with an oversized cylindrical bulb whose rate of cooling from 38°C to 35°C was assumed to be proportional to the cooling power of the atmosphere (this temperature range was chosen to represent cooling in humans).

Other workers using the katathermometer include Bedford and Warner 1933, Weiss 1925, Bradtke 1937, and Lehmann 1936 (all referenced in Stone, 1943). All calculate different constants for the heat balance equation (see Table 1), but only Lehmann rejects the square root of the wind speed, concluding that the exponent (m) should be 0.622 for wind speeds less than 15 m/sec and 0.7 ≈ 0.8 for higher speeds.

It should be noted that human body cooling computed from katathermometer readings was 2 to 3 times greater on average than the actual (directly measured) human cooling (Stone, 1943).

The frigorimeter was another instrument used to calculate the cooling power of the atmosphere. It was similar to the katathermometer, but consisted of a black, nearly solid copper sphere (7.5 cm in diameter) whose temperature was kept at 37°C (body core temperature), by an electric heater. The current needed to maintain this temperature was assumed to be a measure of cooling power. The main user was Dorno who invented the instrument in 1925, and Buttner (see Stone 1943). The formulae obtained take the same form as Hill's equation, though the constants and wind speed exponent vary (see Table 1).

Other workers interested in obtaining an equation to quantify the cooling power of the wind had realised that the square root of the wind speed was only the first term in a series, and introduced a first power term. (Plummer,1944 and Siple and Passel, 1945). Plummer produced the following equation (expressed in units to allow the first 2 terms to be compared with the formulae given in Table 1).

$$H = (10.0086 + 0.231\ V^{0.5} + 0.05175\ V)\ (33 - ta)$$

where H = rate of heat loss ($mcal/cm^2/sec$)

V = wind speed (m/sec)

33 = surface temperature of object (°C)

ta = ambient air temperature (°C)

COMPARISON OF VARIOUS EXPERIMENTAL FORMULAE FOR

$H = (a + bV^m)(ts - ta)^p$

INVESTIGATOR	a	b	m	ts	p	H*
Hill (1)	0.20	0.40	0.5	36.5	1.0	+
Hill (2)	0.13	0.47	0.5	36.5	1.0	123.6
Bedford-Warner	0.123	0.465	0.5	36.5	1.0	122.0
Weiss	0.14	0.49	0.5	36.5	1.0	129.3
Bradtke	0.10	0.403	0.5	36.5	1.06	137.2
Lehmann (1)	0.113	0.34	0.622	36.5	1.0	117.3
Lehmann (2)	0.113	0.34	0.7 or 0.8	36.5	1.0	++
Dorno (1)	0.22	0.25	0.667	33.0	1.0	84.9
Dorno (2)	0.22	0.20	0.769	36.5	1.0	90.0
Buttner	0.23	0.47	0.52	36.5	1.0	118.7

\+ Hill (1) for $V < 1$ m/sec

Hill (2) for $V > 1$ m/sec

++ Lehmann (2) $V > 15$ m/sec

*H in mcal/cm^2/sec computed for ta = -40°C and V = 10 m/sec.

To convert to W/m^2, multiply by 41.76.

TABLE 1 (From Court, 1948)

Plummer assumed that the rate of heat loss from a human body is about the same as heat loss from a cylinder 3 inches in diameter, but with the same surface area as the body.

The Siple and Passel formula was developed in Antarctica in the 1940's and is described in detail in section 2.1. This formula gained acceptance and is still widely used. Since the last World War the other wind-chill equations that have been proposed have been mostly variations of the Siple and Passel one; these and others are described in section 2.3.

A notable exception to these formulae of the Siple and Passel type was one due to Steadman, based upon the concept of a clothed person in thermal equilibrium (Steadman, 1971). The Steadman formula is more relevant to people working outdoors, since it incorporates clothing thickness and physical activity (see section 2.2 for a detailed description).

A yet more complex formula has been developed by Beal (see section 2.3), following Steadman's work.

Of the formulae described those in widespread use in the English speaking world are the empirical one due to Siple and Passel, and the theoretical one due to Steadman.

2.1 Siple and Passel formula

This wind-chill formula was developed from experiments conducted in Antarctica during the winter of 1941 (Siple and Passel, 1945). Measurements were made of the time required to freeze 250g of water in a plastic cylinder, in a variety of wind speeds, and temperatures. The rate of heat loss was assumed to be proportional to the difference in

temperature between the cylinder, and the temperature of the surrounding air. 89 separate results were obtained of which 56 were used to produce the following equation (note the different units to those used in Table 1)

$H = (10\sqrt{V} + 10.45 - V)(33 - ta)$

where

H = cooling power of the atmosphere (K cal/m^2/hour) *

V = wind speed (m/sec)

ta = air temperature (°C)

33 = bare skin temperature (°C)

The bare skin temperature of 33°C was chosen to be consistent with the proposal made that clothing insulation be based upon the "clo" unit (Gagge, Burton and Bazett, 1941) ie 1 clo is the amount of clothing required to keep a body in comfortable thermal equilibrium, with a dry-bulb temperature of 21°C and relative humidity of less than 50% when the average bare skin temperature is 33°C.

The original application of this windchill formula was to predict conditions likely to induce frostbite during army training exercises. Maps of wind-chill indices for the United States, then Canada and, eventually, all continents were prepared as a guide to clothing requirements.

Today, forecasts of wind-chill conditions based on Siple and Passel's work are regularly issued by official meteorological services in the USA and Canada and are commonplace on TV and radio weather broadcasts (N.O.A.A. 1975 and Schlatter, 1981).

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* to convert to W/m^2, multiply by 1.16

The Siple and Passel formula forms the basis of most published tables and nomograms of wind-chill and appears in many papers and text books eg Falkowski and Hastings, 1958; Thomas and Boyd, 1957; Westbrook, 1961; Howe, 1962; NOAA, 1975; Lacy, 1977; Smith, 1979, Schlatter, 1981; Anton, 1981.

Terjung (1966) took the results obtained from the Siple and Passel formula and classified the indices in terms of sensations felt eg -

Wind-chill		Sensation or Result
K cal/m^2/hour	W/m^2	
1000	1160	Very cold
1200	1390	Bitterly cold
1400	1625	Exposed flesh freezes
2000	2320	Exposed flesh (areas of the face) freeze in 1 minute.

The problems of evaluating wind-chill in terms of human sensations were demonstrated in a study of the observations of 35 people during two Canadian winters (Currie, 1951).

The Siple and Passel formula has been criticised on scientific grounds (especially by environmental physiologists) largely because of

1) the lack of a theoretical basis

2) the observational and computational methods upon which it is based.

3) its use in weather conditions other than those during the Antarctica experiments.

4) its relevance to human beings (Molnar, 1960 and Court 1981).

It does not take into account all heat losses from the human body (except convective cooling) and the lack of reference to the amount of clothing worn makes it almost impossible to express the effect of the wind on heat loss from a person (Burton and Edholm, 1955).

Siple himself recommended dropping the units from his wind-chill index calculations and regarding the results simply as numbers for empirical purposes e.g a result obtained from the equation (in the form already indicated) of 1200 would indicate bitterly cold conditions etc. (Molnar, 1960).

Despite these reservations the Siple and Passel formula is still the most widely used wind-chill equation in the English speaking world.

2.2 Steadman's Formula

This wind-chill formula emerged from Steadman's ideas on the thermal equilibrium of the body, ie all heat generated by a body is balanced by heat loss, provided the body is adequately covered with the appropriate thickness of clothing (Steadman, 1971).

Steadman assumes that a healthy adult wearing suitable winter clothing walking at 3 mph (1.3 m/sec) could generate 45 cal/m^2/sec (188 W/m^2). This would be balanced by all losses from the body ie for unit time and area.

Heat Generation = Evaporative loss in breath
+ loss due to heating breath
+ loss from uncovered skin
+ loss from thinly clothed hands and feet
+ loss from fully clothed parts

The body is assumed to be 1.7m high with a surface area of 1.7m^2. The body core temperature is 37°C, the temperature of the skin (adequately covered by clothing) is taken as 33°C (after Gagge 1941) and 30°C is the value taken for the bare skin temperature (which Steadman believes is more consistent with outdoor comfort).

Steadman's thermal equilibrium formula is shown below (units are cal/m^2/sec) *. (Note that his paper incorrectly quoted a temperature of 30°C in the fifth term and that the descriptions of the first two terms were interchanged – these errors have been rectified here).

$$45 = 3.9 + 0.053\ (37 - ta) + \frac{0.03\ (30 - ta)}{R_s} + \frac{0.12\ (30 - ta)}{0.5 + R_s} + \frac{0.85\ (33 - ta)}{R_F + R_s}$$

Each of the 5 terms of the equation relates to the 5 named forms of heat loss indicated previously.

ta = ambient air temperature (°C)

R_F = clothing resistance (m^2sec(°C)/cal)

$\cong {}^{d_F}/_{k_F}$

where ^{d_F} = fabric thickness

^{k_F} = thermal conductivity of the clothing (cal/m^2sec(°C cm^{-1}))

R_s = surface resistance (m^2sec(°C)/cal)

$$= \frac{1}{hr + hc}$$

where hr = heat transfer coefficient of radiation

hc = heat transfer coefficient of convection (cal/m^2sec(°C))

$$hr = 0.0135 \left[4.0 \left(\frac{Ta + 273}{100} \right)^3 + 0.3 \left(\frac{Ta + 273}{100} \right)^2 \right]$$

$$hc = 0.61\ (s^{0.75})$$

s = effective wind speed ie an adjusted 10m wind speed (mph) to represent the wind that would affect a person walking at 3 mph.

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* to convert to W/m^2, multiply by 4.176

The effect of the walkers speed on the relative wind speed is only important in light winds hence there are 2 equations to calculate the effective wind speed, namely

$$S = (V^2 + 10)^{1/2} \quad \text{if } V \geq 6.4 \text{ mph}$$

and $S = (V^2 + 10 + 7\,(6.4 - V)^{1/2})^{1/2}$ if $V < 6.4$ mph.

The expression for wind-chill, ie the heat loss from the unclothed parts of the body is as follows -

$$\frac{(30 - ta)}{R_s}$$ (item 3 in the thermal equilibrium equation)

It is only applicable to exposed bare skin areas which Steadman limits to the face and estimates this to be 3% of the body's surface area.

Steadman's "thermal equilibrium" formula is more relevant to the comfort of persons working outdoors than the Siple and Passel formula as it considers all heat losses from a clothed person and assumes the wind speed to be at person height (1.5-2m), not anemometer height (10m). In addition, calculations can be made of the clothing thickness necessary to maintain comfort.

Steadman also allows for a possible gain in heat by insolation if a person is standing in full sunlight. The equation for this heat gain (which must be deducted from the heat loss equation) is as follows

additional heat gain = α PG

where α = absorptivity of the skin or clothing

P = proportion of the skin or clothing effectively receiving normally incident radiation.

G = insolation (cal/m^2/sec)

The formula is consequently more complicated than that derived by Siple and Passel as it does consider more variables but is yet to be verified by any field observations.

Steadman's formula was used to assess the cooling power of the wind in upland Britain for recreational purposes, and the likely hypothermia affect on people (Smithson and Baldwin, 1979).

In 1979, Steadman published work on the assessment of sultriness, ie the combined effect of high temperatures and high humidities on a person (Steadman, 1979a, 1979b). More recently he has produced results that can be used for both wind-chill and heat stress conditions and the more commonly experienced states between these 2 extremes, and are applicable to all dry bulb temperatures between -40°C and +50°C and wind speeds up to 20 m/sec. (Steadman, 1984).

This new work contains several modifications and corrections to his earlier ideas, but being solely based on clothing resistance sheds little light on the wind-chill of exposed parts of the skin, as Steadman himself admits.

The important changes made in 1984 that affect the wind-chill and thermal equilibrium equation (Steadman, 1971) are summarised below -

a) the skin temperature is not taken as a fixed value of 30°C but is determined from the body core temperature (37°C). (However Steadman does not recommend calculating the surface temperature from the heat balance equation for bare skin if the temperature is less than 0°C, as the exact nature of the response of skin to such conditions is not known. He does not state, however, whether a fixed skin temperature is acceptable at such temperatures).

b) The base wind speed has been changed from 5 mph (2.5 m/sec) at 10m (3 mph at person height) to zero, so that the full cooling effect of the wind is taken into account.

c) the proportion of a body that is clothed is not taken as a constant but recalculated for each temperature and wind speed combination.

d) the amount of heat generated by a person while walking is changed from 188 W/m^2 (1971 paper) to 177.8 W/m^2.

There are many more modifications but they are either of a small magnitude or are relevant only to the higher temperature range and the effect of sultriness.

2.3 Other Post-War Formulae

Many formulae since the 1940's are based on the Siple and Passel equation. Court recalculated the Siple and Passel equation using all the 89 original observations producing the following equation -

$$H = (10.9\ (V)^{0.5} + 9.0 - V)\ (33 - ta) \qquad \text{(Court, 1948)}$$

where H = heat loss ($Kcal/m^2/hour$) *

V = wind speed (m/sec)

ta = air temperature (°C)

To investigate wind-chill during the winter of 1980/1981 Lyall used a simplified version of the Siple - Passel equation -

$$H = ((50V^{0.5}) + 10)\ (30 - tw)\ Kcal/m^2/hour\ * \qquad \text{(Lyall, 1981).}$$

where V is the wind speed in knots and tw is the wet bulb temperature (°C). Lyall used the wet bulb temperature as human skin pores are always perspiring ie the wetted skin layer could be cooled to the wet bulb

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* to convert to W/m^2, multiply by 1.16.

temperature, a lower temperature than the dry bulb. However, in wind-chill cases, sweating is negligible so the use of t_w seems inappropriate. Lyall used 30°C as the skin temperature which is in line with Steadman.

Beal has derived a formula based on heat transfer theory and characteristics intrinsic to the clothed person from which heat must be lost at a rate just sufficient to maintain thermal equilibrium. (Beal, 1974). This formula is similar to Steadman's but incorporates more parameters and consequently the equation is more complex and less practical to implement. Beal attempts to take account of metabolic heat production, radiative exchange with the environment and the sun, heat loss by convection, conduction and heat loss through the lungs, the effect of clothing to reduce heat loss, physiological variables such as age, health, time of food ingestion and time of day, psychological effects such as length of darkness, snow and general state of mind! Beal's equation is as follows -

$$Q = 13.50 + 0.188\ (37 - T) + [0.03/R(V_o, 30, T) + 0.05/(R(V_o, T + 5, T) + 0.18) + 0.07/0.14]\ (30 - T) + 0.85\ (33 - T)/R(V_o, T + 5, T) + R_o) - Q_i$$

where

Q = wind-chill factor (Kcal/m^2/hour).

R = total resistance due to radiation and convection (Kcal/m^2/hour), a function of V_o, T and surface temperature.

T = air temperature (°C)

R_o = resistance of the clothing covering the body. (Kcal/m^2/hour)

Q_i = total heat energy input, based on metabolic rate (which varies with physical activities) and overall resistance. (Kcal/m^2/hour)

V_o = wind speed, adjusted for the average height of a person. (m/sec)

The temperature of the air in the lungs is taken as 37°C, exposed skin temperature is 30°C, and the temperature of the outer surface of the clothing is taken as 5°C higher than the ambient air temperature.

Beal's equation has yet to be verified by experimentation.

Rodriguez adopts an "engineering" approach to the wind-chill problem by considering a two-film model (Rodriguez, 1980) ie a conductive film coefficient inside the skin (h_i), and a convective coefficient for the layer of air outside the skin (h_o). If the body core temperature is fixed at 37°C then the skin surface temperature (t_s) is a variable that depends on the outside temperature and the convective coefficient of heat loss from the skin (h_o) which depends on the wind speed. This means that a realistic skin temperature can be calculated, unlike the Siple and Passel formula which assumes a constant skin temperature of 33°C. Rodriguez states that if the skin really stayed at this temperature no discomfort would be felt. Rodriguez derives the following equations -

Heat loss = $U(37 - ta) = ho\ (ts - ta) = hi\ (37 - ts) = (ho^{-1}+hi^{-1})^{-1}(37-ta)$

where the overall coefficient U is the coefficient of conduction.

If it is assumed the frost bite occurs at some low skin temperature (ts), then a critical wind speed can be calculated for each air temperature using these equations. However, Rodriguez does not consider the process of vaso-constriction when calculating the skin temperature, ie when the brain senses reduced blood temperature, blood is diverted from the exterior by the constriction of peripheral blood vessels, in order to reduce heat loss, thus maintaining the temperature of vital organs (brain, heart and lungs) at 37°C, at the expense of more "superficial" areas such as hands and feet.

2.4 Differences between the Siple and Passel Formula and Steadman's 1971 formula

There are several notable differences between these formulae.

The Siple and Passel formula provides a measure of convective cooling which is the major source of heat loss from a body, but the omission of any clothing consideration, will produce an overestimate of heat loss from a clothed person.

By contrast, Steadman considered all the physiological heat losses and pointed out that the wind-chill part of his formula should be used to relate to areas of exposed skin of a clothed person, eg the face, amounting to about 3% of the total area.

The temperature chosen to represent this bare skin, is different in the 2 equations, 33°C in Siple and Passel's and 30°C in Steadman's.

Siple and Passel chose 33°C to be consistent with the "clo" unit, although Siple admits that the temperature may be lower, about 32°C. Steadman believes a bare skin temperature of 33°C is too high, ie heat loss from exposed areas of a body is lower than a formula based on 33°C would indicate.

The wind speed used in the two equations is different. The Siple and Passel formula is not associated with a wind speed at any particular height and so it is almost always used with that measured at the standard height of 10m above ground level. The Steadman formula uses a wind speed that is more relevant to a person 1.7m tall, by reducing the wind speed measured at 10m using a power law relationship. Steadman's formula also takes into account the walking speed of the person.

FIGURE 1

A COMPARISON BETWEEN THE SIPLE-PASSEL AND STEADMAN WIND CHILL INDICES USING A FIXED AIR TEMPERATURE OF -2°C AND VARIOUS WIND SPEEDS

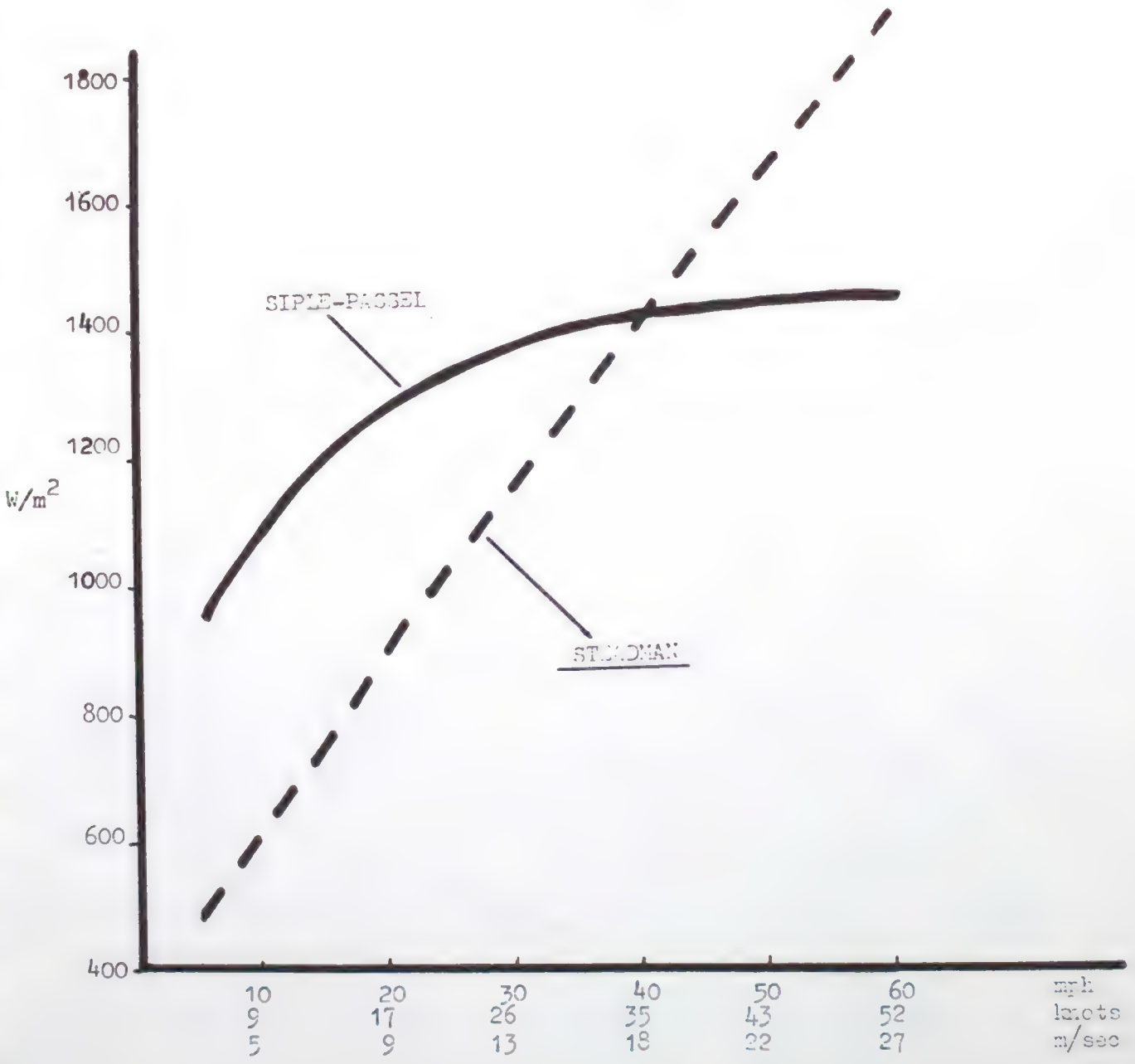


FIGURE 2

COMPARISON BETWEEN THE SIPLE-PASSEL AND STEADMAN WIND CHILL INDICES USING FIXED WIND SPEEDS AND VARIOUS AIR TEMPERATURES

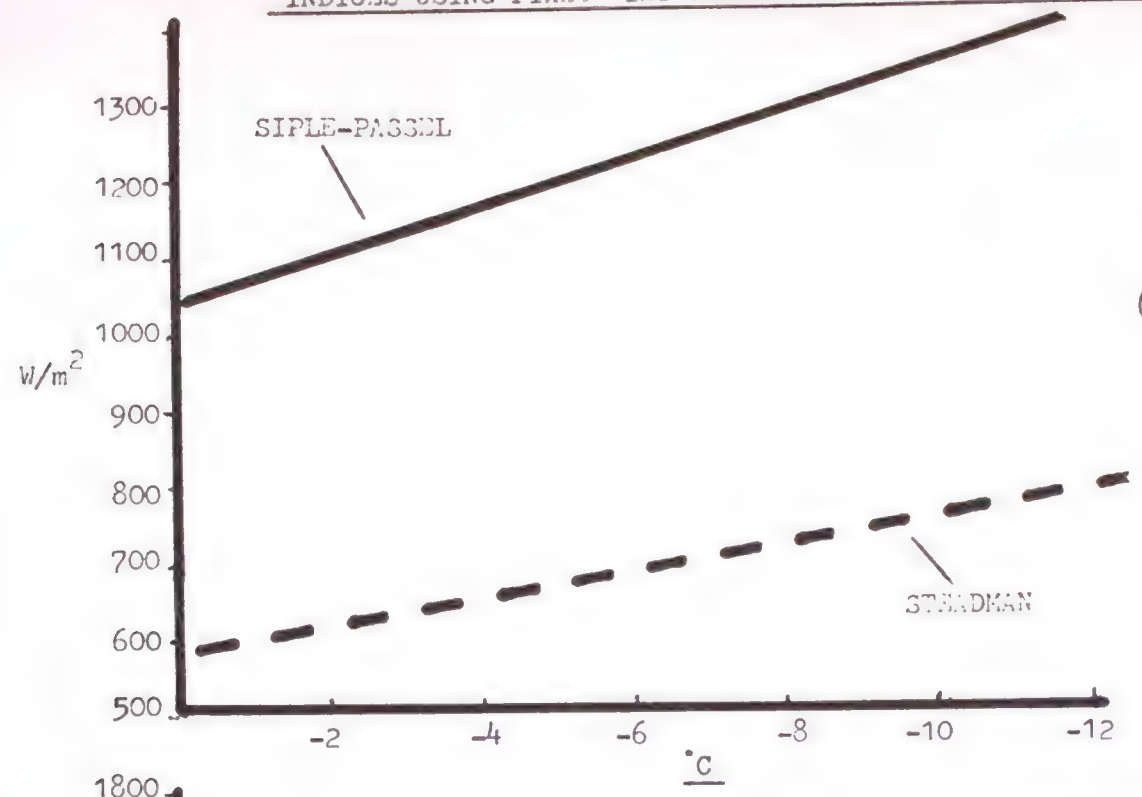


Fig. 2a

10 m.p.h.
(9 knots or 5m/sec)

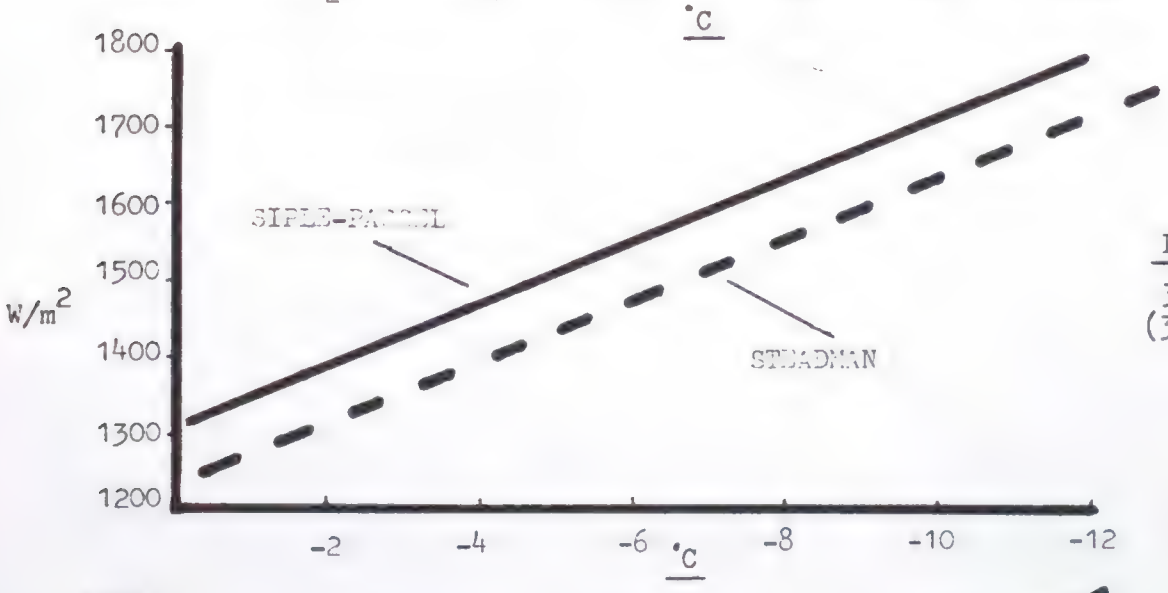


Fig.2b

35 m.p.h.
(30 knots or 16m/sec)

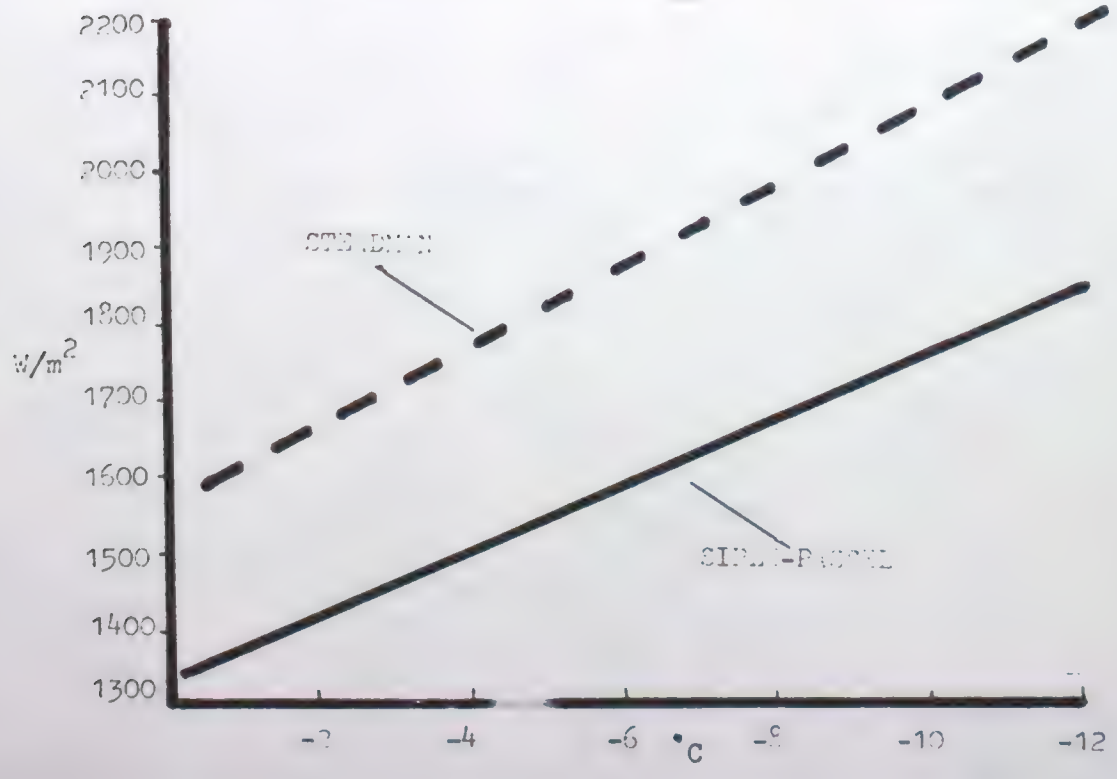


Fig.2c

50 m.p.h.
(43 knots or 22m/sec)

The Siple and Passel formula indicates that heat loss reaches a maximum at a wind speed of 25 m/sec (56 mph) a speed twice as great as any measured during the Antarctic experiments) then diminishes at higher wind speeds (see figures 1 and 2). The cooling process at higher wind speeds is not accounted for. The windchill part of Steadman's formula produces wind-chill indices that increase with wind speed approximately linearly (see Figure 1). Both formulae produce the same results at a wind speed of about 17 m/sec (38 mph). Experience of polar explorers suggests that high wind speeds rather than low temperatures are more limiting to outdoor activity (if appropriate clothing is used). See Figures 2a-c.

3. Wind-chill Equivalent Temperature

A certain combination of wind speed and temperature is associated with a certain rate of heat loss. The same heat loss may also be produced by combining a reference wind speed (eg a person's walking speed) with a different temperature, known as the wind-chill equivalent temperature. By using this, the chilling effects of the wind may be expressed in terms of the lower temperature needed to produce the same sensation for a person walking in calm conditions. Tables 2 and 3 show equivalent temperatures calculated from the Siple and Passel formula and the Steadman (1971) formula. Siple and Passel's equivalent temperatures relate to bare skin areas while Steadman's equivalent temperatures are based on the thickness of clothing required to insulate 85% of the body's surface.

Table 4 shows apparent temperatures from Steadman's 1984 paper. The combined effect of all the changes to his earlier work does not alter the equivalent temperatures by more than 2°C. A humidity increment is also included. Table 5 shows the gain in apparent temperatures at various wind speeds, if the person is standing in full sunshine.

The Siple and Passel equivalent temperatures and those of Steadman (1971) use a reference wind speed of 4 or 5 mph. These formuale are not applicable for wind speeds below the base since they produce the disturbing result of increasing the equivalent temperature above the air temperature at such wind speeds. Most published tables of wind-chill equivalent temperatures based on the above two formulae do not quote equivalent temperatures for calm conditions (Schlatter, 1981). However this anomaly does not exist in Steadman's 1984 figures because the reference wind speed is zero.

The characteristics of the wind-chill calculation, as shown in figures 1 and 2 are reflected in the equivalent temperature tables 2 and 3 ie Siple and Passel's formula produces equivalent temperatures that are more sensitive to changes in the lower wind speed ranges than those in the higher ranges.

The two formulae (Siple and Passel, & Steadman 1971) produce different equivalent temperatures for the same combinations of wind speed and temperature eg at 20°F (-6.7°C) and 20 mph (9 m/sec),

Siple and Passel's equivalent temperature = -5°F (-20.6°C) (see Table 2b)

Steadman's equivalent temperature = +5°F (-15.0°C) (see Table 3)

The reference walking speed used to calculate the equivalent temperature appears to differ in different publications. Wind-chill equivalent temperatures tables derived from the Siple Passel formula use a reference speed of 4 mph (NOAA, 1975 and Schlatter, 1981). However Steadman's wind-chill equivalent temperature table (Steadman, 1971) uses a reference speed of 5 mph and in the same publication prints a table of Siple and Passel equivalent temperatures also with a reference speed of 5 mph, so that the 2 tables can be compared (5mph at 10m is equivalent to 3mph at 1.7m).

A difference of 1 mph in the reference speed in the Siple-Passel formula produces differences of up to 8°F eg. with a reference speed of 4 mph, a wind-chill equivalent temperature of -21°F (-29.4°C) is produced from a combination of 0°F (-17.8°C) and 10 mph (4.5 m/sec); the same combination produces an equivalent temperature of -15°F (-26.1°C) with a reference speed of 5 mph (Driscoll, 1983) - see Tables 2a and 2b.

Included in Steadman's 1984 paper are simplified equations for calculating the apparent temperature, which previously had been very difficult to obtain using Steadman's 1971 formula. Multiple regression analyses were undertaken on 3 sets of 120 pairs of results using the 1984 formula, isolating the separate effects of wind, humidity and sunshine on temperature ⁴ see Table 6.

The figure in brackets below each term is the percentage of total variance explained by the parameter.

These equations make estimates of equivalent temperatures fairly simple to calculate. The statistics have produced some unexpected factors and signs. The factor connected with the air temperature is not 1 - it might have been expected that the equations would use the basic air temperature and then subtract or add the various effects of wind, humidity or sunshine. However the body temperature does not appear as a variable in the equations which may explain the air temperature factor. Also the sign for the humidity factor contradicts theory, since for "cold" conditions a negative contribution from humidity would be expected, ie to lower the apparent temperature. However, the humidity effect at low temperatures is very small. It is more important, though, at higher temperatures where it does have a larger positive effect at 70%+ which presumably justifies the existance of a positive humidity contribution. Finally the negative effect of the fraction of direct solar radiation on apparent temperature in equation 2 would also appear contradictory.

Forecasts of equivalent temperatures are regularly issued by meteorologists in North America where the harsh winter climate warrants a more relevant indication of how cold it will feel outdoors. Usually, it is

TABLE 2 WIND CHILL EQUIVALENT TEMPERATURES (°C) USING SIPLE-PASSEL EQUATION

Table 2a - derived from Schlatter, 1981 using a reference speed of 4 mph

Wind speed (kn)	(mph)	(m/sec)	Air temperature °C 6	3	0	-3	-6	-9	-12	-15	-18	-21
3	4	2	6	3	0	-3	-6	-9	-12	-15	-18	-21
6	7	3	3	-1	-4	-7	-11	-14	-18	-21	-24	-28
12	13	6	-2	-6	-10	-14	-18	-22	-26	-30	-34	-38
17	20	9	-6	-10	-14	-18	-23	-27	-31	-35	-40	-44
23	27	12	-8	-12	-17	-21	-26	-30	-35	-35	-44	-48
29	33	15	-9	-14	-18	-23	-27	-32	-37	-41	-46	-
35	40	18	-10	-14	-19	-24	-29	-33	-38	-43	-	-
41	47	21	-10	-15	-20	-25	-29	-34	-39	-	-	-

Table 2b - derived from Steadman, 1971 using a reference speed of 5 mph

Wind speed (kn)	(mph)	(m/sec)	Air temperature °C 0	-1	-2	-3	-4	-6	-8	-10	-12	-14	-18	-21
4	5	2	0	-1	-2	-3	-4	-6	-8	-10	-12	-14	-18	-21
9	10	5	-6	-7	-8	-9	-11	-12	-14	-17	-20	-22	-26	-31
13	15	7	-9	-11	-12	-13	-14	-16	-19	-22	-24	-28	-32	-35
17	20	9	-12	-13	-14	-16	-18	-19	-22	-25	-28	-31	-35	-40
22	25	11	-14	-15	-16	-18	-19	-21	-24	-28	-31	-34	-38	-
26	30	13	-15	-16	-18	-19	-21	-23	-26	-29	-33	-36	-	-
30	35	16	-16	-17	-19	-21	-22	-24	-27	-31	-34	-	-	-
35	40	18	-17	-18	-20	-22	-23	-25	-28	-32	-	-	-	-

TABLE 3 WIND CHILL EQUIVALENT TEMPERATURES (°C) USING STEADMAN'S EQUATION

Wind speed (kn)	(mph)	(m/sec)	Air temperature °C 0	-1	-2	-3	-4	-6	-8	-10	-12	-14	-18	-21
4	5	2	0	-1	-2	-3	-4	-6	-8	-10	-12	-14	-18	-21
9	10	5	-3	-4	-5	-6	-7	-9	-11	-13	-16	-18	-22	-26
13	15	7	-4	-6	-7	-8	-10	-11	-14	-17	-19	-22	-26	-30
17	20	9	-6	-8	-9	-11	-12	-13	-17	-19	-22	-25	-30	-34
22	25	11	-8	-9	-11	-13	-14	-16	-19	-22	-25	-28	-33	-
26	30	13	-10	-11	-13	-14	-16	-17	-21	-24	-28	-31	-	-
30	35	16	-11	-12	-14	-16	-18	-19	-23	-27	-31	-	-	-
35	40	18	-12	-14	-16	-17	-19	-21	-25	-29	-	-	-	-

(derived from Steadman, 1971
using a reference speed of 5 mp

TABLE 4 WIND-CHILL EQUIVALENT TEMPERATURES USING STEADMAN'S 1984 EQUATION

at 10 metres

TEMP. C	WIND SPEED 2	4	6	8	10	12	15	20 M/SEC
-40	-41.7	-46.7	-50.9	-54.5-	-58.0	-61.0	-64.6	-69.5+
-35	-36.6	-41.3	-45.3	-48.8	-52.1	-54.9	-58.3	-62.7
-30	-31.6	-36.0	-39.8	-43.1	-46.2	-48.8	-52.0	-56.4
-25	-26.5+	-30.6	-34.2	-37.3	-40.2	-42.7	-45.7	-49.8
-20	-21.4	-25.2	-28.6	-31.5-	-34.3	-36.6	-39.3	-43.1
-15	-16.2	-19.8	-23.0	-25.7	-28.2	-30.3	-32.8	-36.3
-10	-11.1	-14.4	-17.3	-19.8	-22.1	-24.0	-26.3	-29.5+
-5	-6.0	-8.9	-11.6	-13.8	-15.8	-17.6	-19.7	-22.6
0	-0.9	-3.5-	-5.8	-7.8	-9.6	-11.1	-13.0	-15.5+
2	1.1	-1.3	-3.5-	-5.4	-7.1	-8.5-	-10.3	-12.6
4	3.2	0.8	-1.2	-3.0	-4.6	-6.0	-7.6	-9.8
6	5.2	3.0	1.1	-0.6	-2.1	-3.4	-4.9	-7.0
8	7.3	5.2	3.4	1.8	0.4	-0.8	-2.2	-4.1
10	9.3	7.4	5.7	3.2	2.9	1.8	0.4	-1.3
12	11.4	9.6	8.0	6.7	5.5-	4.5-	3.3	1.6
14	13.4	11.8	10.3	9.0	7.9	7.0	5.9	4.4
16	15.4	13.8	12.4	11.2	10.3	9.4	8.4	7.1
18	17.4	15.9	14.6	13.5-	12.6	11.9	10.9	9.8
20	19.5-	18.0	16.8	15.8	15.0	14.3	13.5+	12.5-
22	21.5+	20.2	19.0	18.2	17.4	16.8	16.1	15.0
24	23.6	22.4	21.4	20.6	19.8	19.3	18.6	17.7
26	25.6	24.6	23.7	23.0	22.3	21.8	21.2	20.5-
28	27.7	26.8	26.1	25.5+	25.0	24.7	24.2	23.5-
30	29.8	29.1	28.6	28.2	2.8	27.6	27.2	26.8

TABLE 5 INCREASE IN EQUIVALENT TEMPERATURES DUE TO FULL SUNSHINE

(STEADMAN 1984)

Dry-bulb temperature (°C)	Wind speed ($m\ s^{-1}$) 0	2	4	6	8	10	12	15	20
-40	7.2	6.8	5.7	4.7	4.0	3.2	3.0	2.9	2.4
-20	7.4	7.0	5.9	5.0	4.3	3.6	3.4	3.1	2.7
0	7.4	7.0	6.0	5.2	4.5	3.8	3.6	3.4	3.0
20	8.5	8.3	7.4	6.5	5.5	4.6	4.3	3.8	3.3
30	8.3	8.1	7.2	6.6	6.2	5.9	5.6	5.3	4.9

In the Southern Hemisphere the effect of winter sunshine is 6% lower.

(1) Assuming full sunshine value of 135 W/m² at base humidity

(2) Note. Effects are pupational to Qg

(3) At night Qg is negative (say -20 w/m²) or in twilight

TABLE 6: SIMPLIFIED EQUATIONS FOR CALCULATING EQUIVALENT TEMPERATURES

(STEADMAN, 1984)

Conditions	Equations	Residual Standard Deviation
SHADE	$\tau = -2.7 + 1.04\ Ta + 2.0\ Pa - 0.65\ v_{10}$ (98.9%) (0.5%) (0.5%)	0.44
SUN (using actual measured solar quantities)	$\tau = 4.5 + 1.02\ Ta - 1.00 v_{10} + 2.8 Pa - 5.8\ S_D + 0.0054\ (Q_D + Qd)$ (98.3%) (0.7%) (0.4%) (0.3%) (0.04%)	0.54
SUN (deriving solar quantities)	$\tau = -1.8 + 1.07 Ta + 2.4\ Pa - 0.92\ v_{10} + 0.044\ Qg$ (98.3%) (0.7%) (0.4%) (0.4%)	0.51

where τ = apparent temperature (°C)

Ta = ambient air temperature (°C)

Pa = vapour pressure of the air (KPa)

V_{10} = wind speed at 10m (m/sec)

S_D = fraction of solar radiation, on horizontal surface, that is direct.

Q_D = heat transfer rate per unit area of direct insolation on a horizontal surface (W/m^2).

Q_d = heat transfer rate per unit area of diffuse insolation on a horizontal surface (W/m^2).

Q_g = Heat transfer rate of net extra radiation per unit area of body surface (W/m^2).

the Siple and Passel equivalent temperatures that are quoted but the limitations of these are not conveyed eg their applicability to bare skin areas only.

During the winter of 1984/85 weather forecasters in the UK started quoting equivalent temperatures and this is expected to be a growing trend.

4. Applications in the Construction Industry

4.1 Weather interference with construction operations

The chilling effects of strong cold winds can interfere with the comfort and dexterity of workers undertaking a wide range of outdoor operations as well as, in particular, the successful execution of welding and the laying of rolled asphalt surfaces. These have been examined in a Building Research Establishment report 'Climate and Construction Operations in the Plymouth area' (in course of preparation), which gives monthly analyses of the number of working hours affected at Plymouth during the period 1957-1981.

Comfort and dexterity are deemed to be affected when either precipitation is falling at a moderate rate (0.5 mm/hr or more) or when the heat loss from uncovered skin (calculated using Steadman's 1971 formula) is 500 W/m^2 (430 $KCal/m^2/hr$) or more. Steadman's formula was chosen in preference to that due to Siple and Passel because it gives a better representation of people working (see section 2.2).

The difficulty of preheating steel prior to welding when chilling winds are blowing was considered in terms of the number of working hours when the mean Siple-Passel wind-chill index is 1200 W/m^2 (1032 $KCal/m^2/hr$) or more. Definition of a general threshold is difficult since the amount of preheating depends on steel grade, type of electrode and thickness of members to be joined (1200 W/m^2 is usually considered as 'very cold' in physiological terms). The Siple-Passel formula was preferred in this case because it is more appropriate for the cooling of materials than the Steadman formula (see section 2.1), although it was recognised that steel will be at a different temperature to human skin. Since precipitation also affects welding (any moisture present when a weld is being formed may cause

weakening of the joint), both precipitation and wind-chill were taken into account when preparing Figure 3, the result of an analysis for Plymouth, 1957-1981. This type of histogram may be prepared for any meteorological station with a long record of hourly data; of course, at most of the other stations wind-chill will be a more significant factor than it is at Plymouth.

The effect of wind-chill on construction processes is discussed by Lacy (1977), using the Siple-Passel formula. He presents frequency analyses of wind-chill for 4 places for January 1961, and it is now possible to produce supplementary histograms using data recorded throughout several winters. These are given in Figure 4, with the station at Abbotsinch being substituted for the nearby one at Renfrew (now closed), and the calculations of wind-chill being made using hourly mean wind speeds and hourly temperatures.

The effects of the weather on the productivity of construction workers has been considered by Koehn and Brown (1985) and a table of productivity as a function of temperature and humidity is proposed by them.

4.2 Building design and layout

A knowledge of the likely direction and strength of chilling winds is important when deciding upon the layout of buildings and outdoor facilities. Protective measures, for example the placing of wind breaks, may be taken for energy conservation or amenity reasons. (Dodd, 1985).

The Meteorological Office has programs that analyse hourly data sets of wind speed, wind direction and air temperature in terms of the Siple-Passel and Steadman (1971) wind-chill formulae. These programs produce frequency tables of chill index in 100 W/m^2 ranges versus wind

direction in 30° sectors. Examples are given in Tables 7-11, produced using hourly data recorded at 5 stations during the months October - April of various periods in the Siple-Passel formula.

From such frequency tables it is possible to choose a wind-chill threshold, such as 900 W/m^2 which corresponds roughly with 'cold' in physiological terms, and assess each sector in terms of the percentage of time that such a threshold is exceeded. From these percentages, a wind-chill 'rose' may be produced for comparison with a wind speed 'rose' (Figures 5a and 5b). Such comparisons highlight differences between the direction of the prevailing wind and the main directions of the chilling winds, as in the case of the Heathrow example. A similar comparison using indices produced from the Steadman (1971) formula which exceed 500 W/m^2 (Figure 5c) does not show such a marked contrast with the wind rose. This is because the Steadman formula is more sensitive to higher wind speeds than the Siple-Passel one and so the windy south-westerly sector partly regains its prominence when using the 500 W/m^2 threshold (see section 2.4).

For many stations differences between wind and wind-chill 'roses' are less marked than at Heathrow when a threshold corresponding to 'cold' is chosen; the pair of 'roses' for Elmdon given in Figures 6a and 6b are more typical. However, as one might expect, the higher the threshold the more contrast there is, with indices classified 'very cold' or 'bitterly cold' being mainly associated with winds from NW, N, NE and E directions; the pair of 'roses' using a chill threshold of 1100 W/m^2 (946 $KCal/m^2/hr$) for Elmdon is given in Figure 6c.

Perhaps the most useful type of presentation for design purposes is one showing the percentage of time that a certain chill index is likely to be associated with a wind blowing from a certain direction. Figure 7 shows

FIGURE 3

Upper quintile, Average and Lower quintile of working hours when welding is affected by the weather (any precipitation or mean Siple-Passel wind chill index > 1200 W/m^2) at Plymouth during the period 1957-1981.

The upper quintile is exceeded on average 1 year in 5 and the lower quintile is not reached on average 1 year in 5.

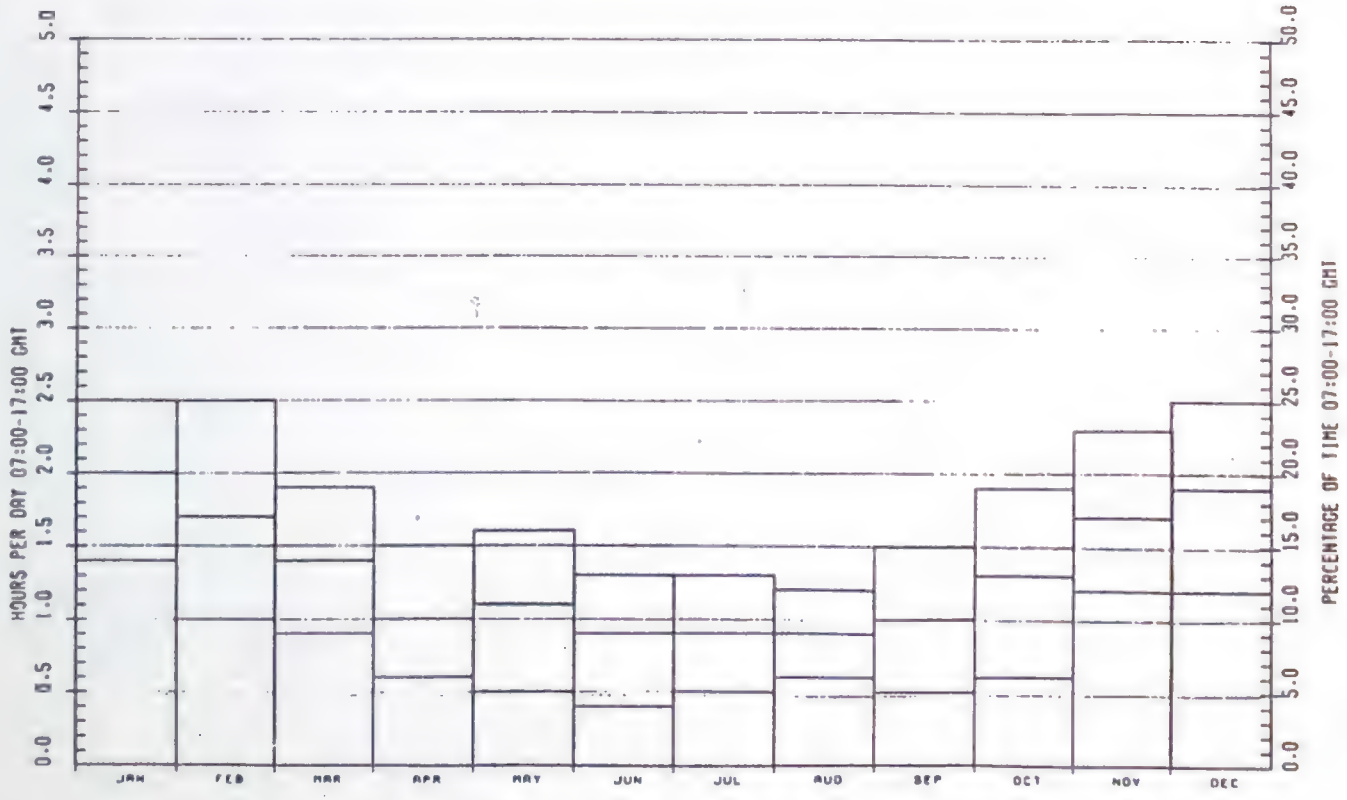


FIGURE 4

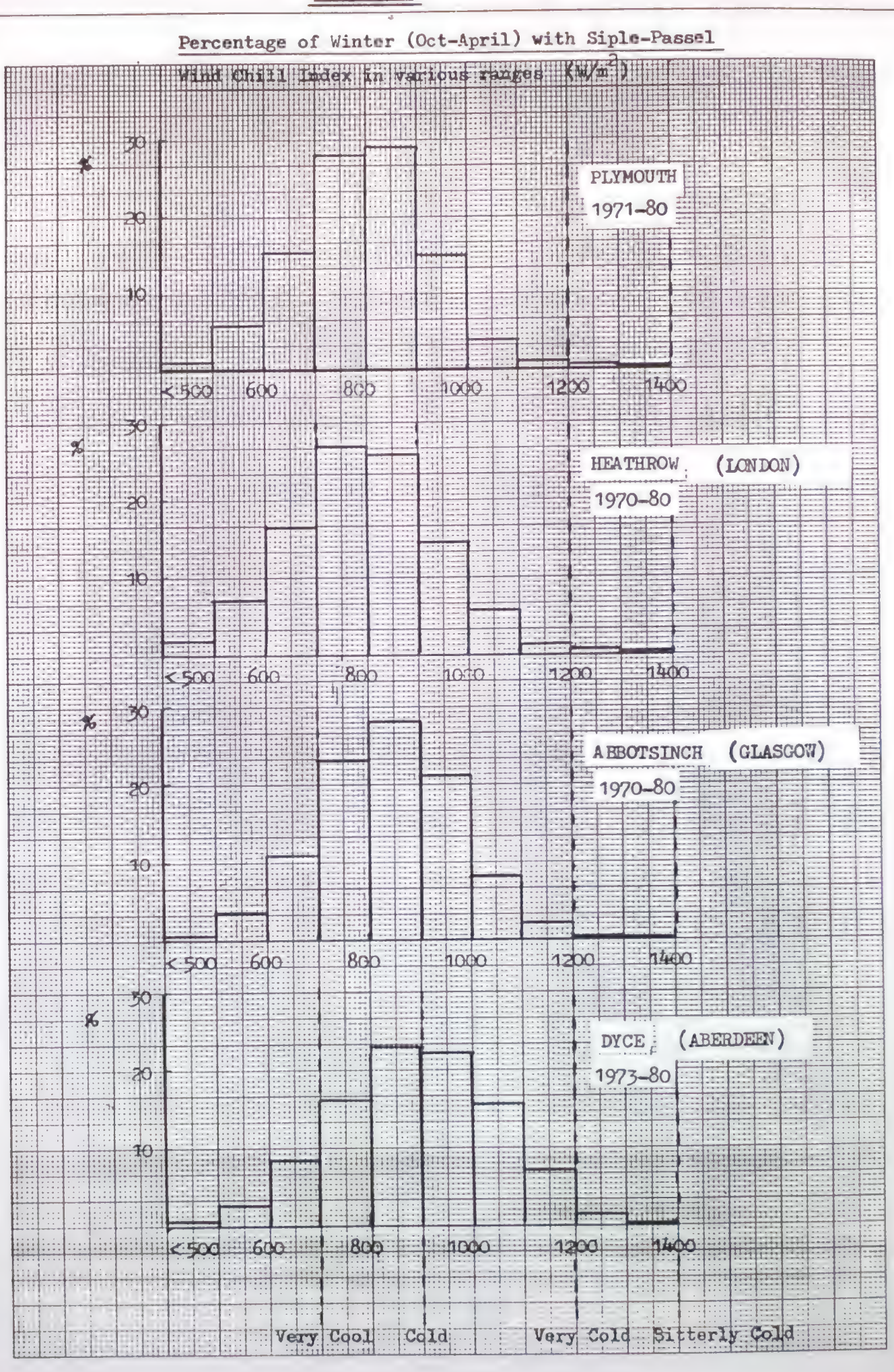

Percentage of Winter (Oct-April) with Siple-Passel Wind Chill Index in various ranges (kW/m²)
PLYMOUTH
1971–80
HEATHROW (LONDON)
1970–80
ABBOTSINCH (GLASGOW)
1970–80
DYCE (ABERDEEN)
1973–80
%
30
20
10
< 500
600
800
1000
1200
1400
Very Cool
Cold
Very Cold
Bitterly Cold

TABLE 7

Meteorological Office

FREQUENCY OF MEAN HOURLY WIND CHILL INDEX (Siple-Passel Formula)

at PLYMOUTH for OCTOBER TO APRIL DURING 1971-1980

Height of Vane or Cups
- Above Ground
- Above Building
- Effective Height 13 m

Wind Chill Index W/m²	Degrees (true)												All Dir.
	350-10	20-40	50-70	80-100	110-130	140-160	170-190	200-220	230-250	260-280	290-310	320-340	
< 500	11	18	22	74	57	33	22	59	43	35	26	26	426
500-599	159	128	204	417	327	229	148	313	262	253	221	220	2881
600-699	491	388	653	1035	676	387	490	789	826	704	579	658	7676
700-799	832	602	1197	1478	857	741	789	1416	1831	1752	1307	1063	13865
800-899	850	688	1089	1345	746	687	977	1511	2081	1979	1331	1122	14406
900-999	618	507	729	907	356	292	516	672	751	864	733	619	7564
1000-1099	207	271	426	323	92	90	70	70	73	135	127	164	2048
1100-1199	21	35	150	105	15	6	5	3	1	24	26	33	424
1200-1299	11	19	37	71									138
1300-1399	8	2	9	13									32
1400-1499			5										5
1500-1599													
1600-1699													
≥ 1700													
Total	3208	2658	4521	5768	3126	2465	3017	4833	5868	5746	4350	3905	49465
% ≥ 900	8.5	8.2	13.3	13.9	4.5	3.8	5.8	7.3	8.1	10.0	8.7	8.0	100%

TABLE 8

Meteorological Office

FREQUENCY OF MEAN HOURLY WIND CHILL INDEX (Siple-Passel Formula)

at LONDON (HEATHROW) for OCTOBER TO APRIL DURING 1970-1980

Height of Vane or Cups — Above Ground ..... ft.
Above Building ..... ft. No. .....
Effective Height 10m

Wind Chill Index W/m^2	Degrees (true)												All Dir.
	350-10	20-40	50-70	80-100	110-130	140-160	170-190	200-220	230-250	260-280	290-310	320-340	
< 500	39	34	53	76	136	134	175	147	131	51	59	44	1079
500-599	153	180	184	306	299	350	443	635	490	272	199	168	3679
600-699	386	514	489	449	523	657	1011	1800	1286	904	548	504	9071
700-799	720	799	680	599	767	1008	1673	2549	2479	2000	1095	817	15186
800-899	790	1118	841	734	783	753	1395	2072	1967	1854	1167	891	14365
900-999	626	860	556	591	417	308	492	637	754	1161	965	651	8018
1000-1099	337	551	316	298	130	97	70	60	133	348	427	360	3127
1100-1199	131	157	181	68	36	14	8	5	18	26	45	83	772
1200-1299	31	56	77	58	5						1	13	241
1300-1399	8	17	10	4	1							2	42
1400-1499			2										2
1500-1599													
1600-1699													
≥ 1700													
Total	3221	4286	3389	3183	3097	3321	5267	7905	7258	6616	4506	3533	55582
% ≥ 900	9.3	13.5	9.4	8.3	4.8	3.4	4.7	5.7	7.4	12.6	11.8	9.1	100%

TABLE 9 Meteorological Office

FREQUENCY OF MEAN HOURLY WIND CHILL INDEX (Siple-Passel Formula)

GLASGOW (ABBOTSINCH) for OCTOBER TO APRIL DURING 1970 – 1980

Height of Vane or Cups — Above Ground ..... / Above Building ..... / Effective Height 10m

Wind Chill Index W/m^2	Degrees (true)												All Dir.
	350–10	20–40	50–70	80–100	110–130	140–160	170–190	200–220	230–250	260–280	290–310	320–340	
< 500	18	29	33	33	31	16	19	24	28	36	25	17	309
500–599	64	139	290	225	133	107	181	152	202	197	157	52	1899
600–699	170	345	873	671	352	229	396	789	873	618	360	132	5802
700–799	265	554	1555	1056	566	437	675	1882	2560	1549	658	204	11961
800–899	293	537	1950	1064	635	530	896	2370	3517	2064	862	312	15030
900–999	268	415	1817	1043	346	266	422	1611	2230	1558	686	331	10993
1000–1099	112	191	870	648	90	66	75	415	790	833	449	144	4683
1100–1199	38	68	279	192	25	13	8	85	106	170	97	28	1109
1200–1299	5	5	86	114				9	3	2	8	1	133
1300–1399		7	27	3					1				38
1400–1499													
1500–1599													
1600–1699													
⩾ 1700													
Total	1233	2290	7780	4949	2178	1664	2666	7337	10310	7027	3302	1221	51957
% ⩾ 900	2.5	4.1	18.2	11.2	2.7	2.0	3.0	12.5	18.5	15.1	7.3	3.0	100%

TABLE 10 Meteorological Office

FREQUENCY OF MEAN HOURLY WIND CHILL INDEX (Siple-Passel Formula)

at ABERDEEN (DYCE) for OCTOBER TO APRIL DURING 1973 – 1980

Height of Vane or Cups — Above Ground ____ / Above Building ____ / Effective Height 10 m

Wind Chill Index W/m^2	Degrees (true)												All Dir.
	350–10	20–40	50–70	80–100	110–130	140–160	170–190	200–220	230–250	260–280	290–310	320–340	
< 500	7	5	4	12	27	20	19	7	12	11	17	14	155
500–599	66	46	39	48	139	182	136	108	79	57	59	51	1010
600–699	223	111	93	199	318	520	547	467	406	249	203	225	3561
700–799	482	187	203	239	433	826	1136	940	861	699	464	457	6927
800–899	495	214	285	282	420	1007	1311	1210	1077	1000	805	675	8781
900–999	362	166	264	332	380	946	1254	967	956	1049	1188	685	8549
1000–1099	292	74	154	234	288	560	804	504	476	766	1222	608	5982
1100–1199	152	27	102	75	38	181	180	103	75	368	812	475	2588
1200–1299	23	29	33	15		6	21	16	11	74	226	133	587
1300–1399	3		2	1						1	12	18	37
1400–1499												3	3
1500–1599													
1600–1699													
⩾ 1700													
Total													
% ⩾ 900	2105	859	1179	1437	2043	4248	5408	4322	3953	4274	5008	3344	38180

TABLE 11

Meteorological Office

FREQUENCY OF MEAN HOURLY WIND CHILL INDEX (Siple-Passel Formula)

at BIRMINGHAM (ELMDON) for OCTOBER TO APRIL DURING 1970 – 1979

Height of Vane or Cups — Above Ground ..... / Above Building ..... / Effective Height 10m

Wind Chill Index W/m^2	Degrees (true)												All Dir.
	350–10	20–40	50–70	80–100	110–130	140–160	170–190	200–220	230–250	260–280	290–310	320–340	
< 500	14	38	71	55	92	109	57	20	26	5	12	12	511
500–599	87	136	208	180	296	401	303	228	209	79	85	105	2317
600–699	287	323	353	300	543	789	667	913	772	305	261	331	5844
700–799	517	568	428	337	664	1172	1263	1944	1598	847	708	657	10703
800–899	618	876	567	327	595	1256	1519	2281	1957	1242	1093	907	13238
900–999	623	735	566	294	588	781	962	1189	1227	805	1092	855	9717
1000–1099	295	465	303	207	232	315	288	229	311	484	769	676	4574
1100–1199	94	129	143	85	93	120	29	27	27	73	190	263	1273
1200–1299	5	18	32	61	15	10	3	2	4	5	13	32	200
1300–1399	23	25		1									49
1400–1499													
1500–1599													
1600–1699													
⩾ 1700													
Total	2563	3313	2671	1847	3118	4953	5091	6833	6131	3845	4223	3838	48426
% ⩾ 900	6.6	8.7	6.6	4.1	5.9	7.7	8.1	9.1	9.9	8.6	13.1	11.5	100%

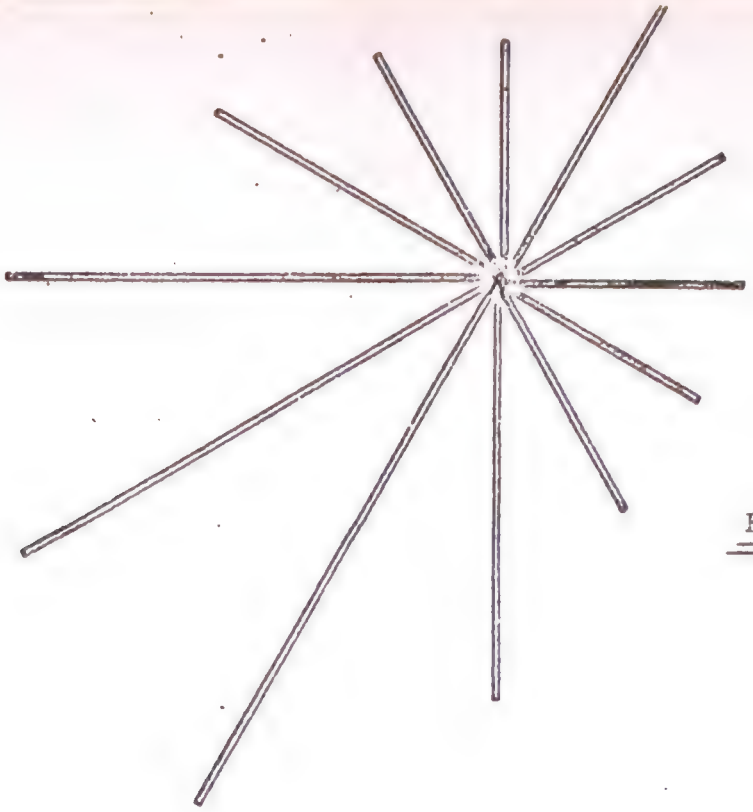


FIGURE 5 a

WIND SPEEDS (OCTOBER-APRIL 1970-1980)
PERCENTAGE OF ALL DIRECTIONS

0 5%

HEATHROW

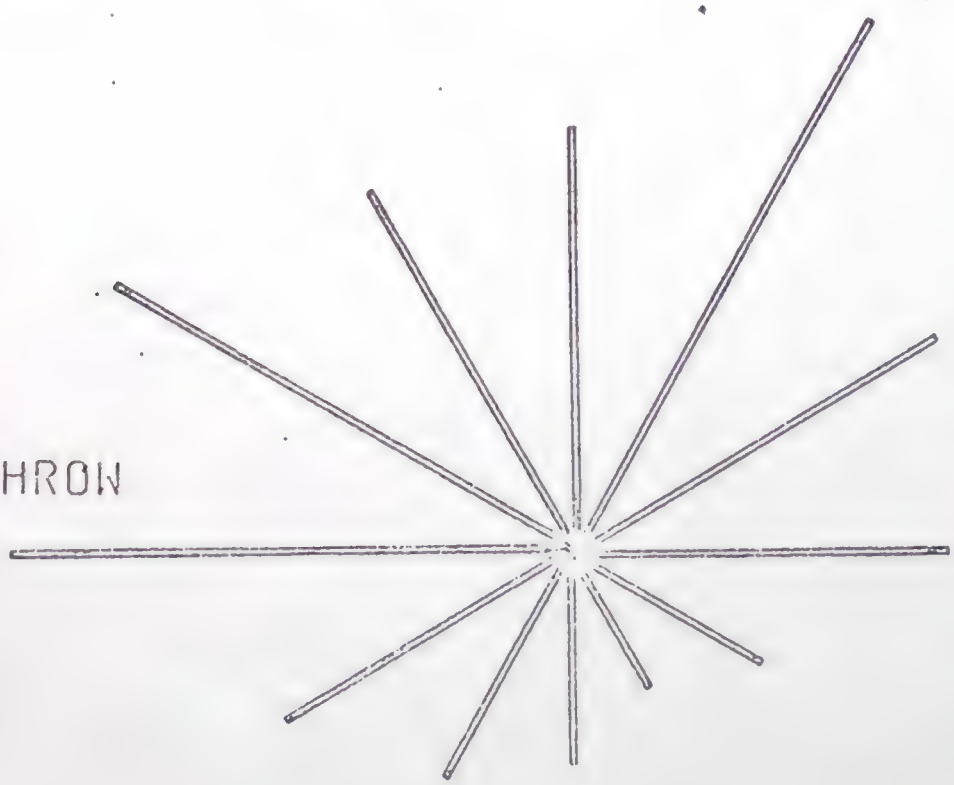
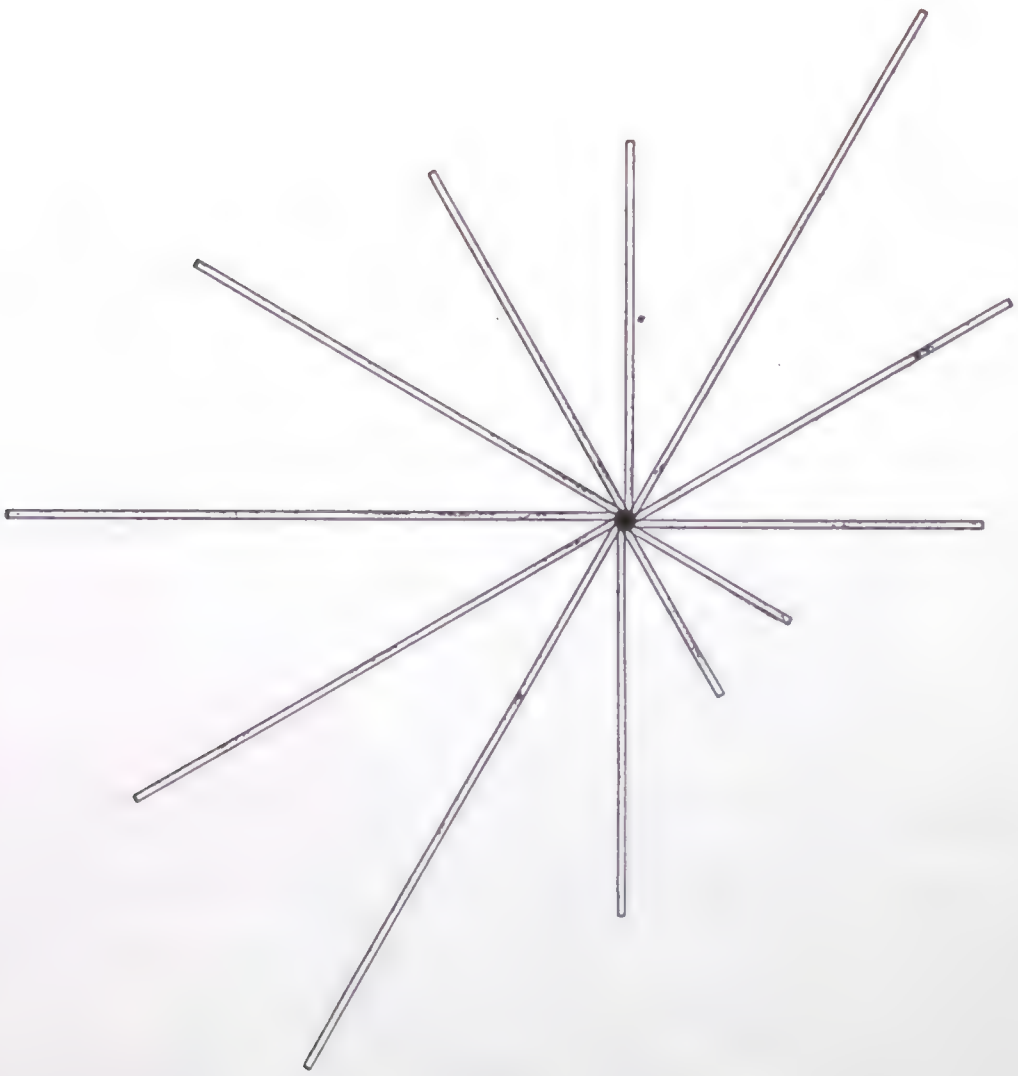


FIGURE 5 b

WIND CHILL INDEX GE 900 W/M2
PERCENTAGE OF ALL DIRECTIONS (OCTOBER- L 1970-1980) 0 5%

FIGURE 5 c

HEATHROW: STEADMAN'S FORMULA



WIND CHILL INDEX GE 500 W/M2

PERCENTAGE OF ALL DIRECTIONS

0 5%

(OCTOBER-APRIL 1970-1980)

FIGURE 6 a

WIND SPEED (OCTOBER-APRIL 1970-1979)
PERCENTAGE OF ALL DIRECTIONS

0 5%

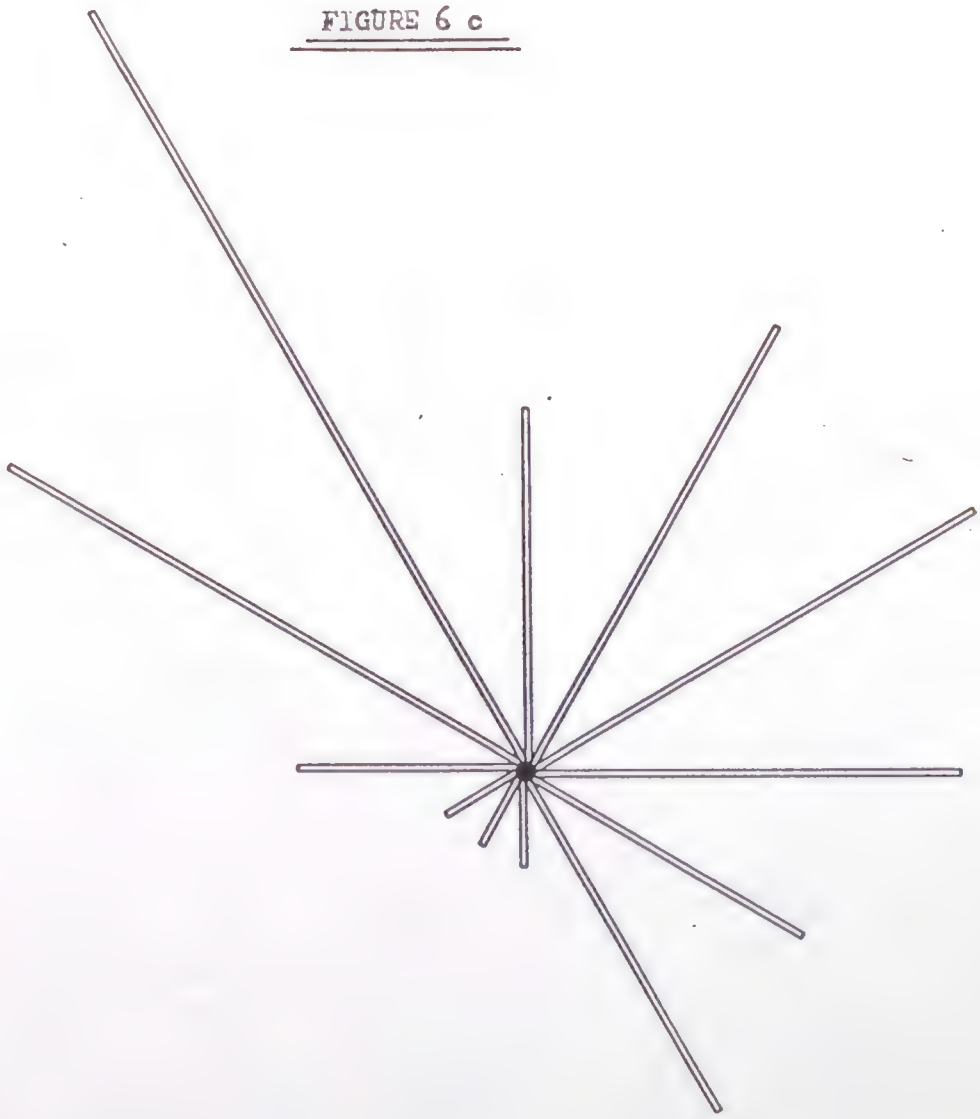
ELMDON

FIGURE 6 b

WIND CHILL INDEX GE 900 W/M2
PERCENTAGE OF ALL DIRECTIONS (OCTOBER-APRIL 1970-1979) 0 5%

FIGURE 6 c

ELMDON



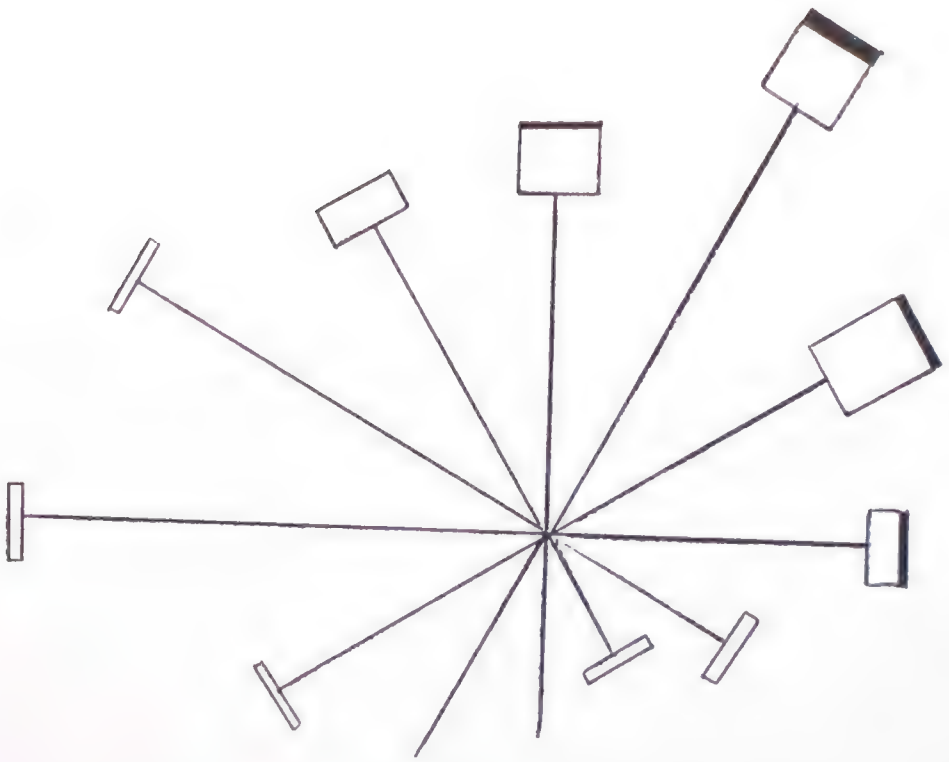
WIND CHILL INDEX GE 1100W/M2

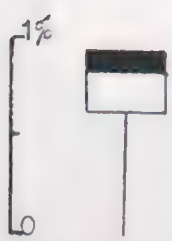
PERCENTAGE OF ALL DIRECTIONS

0 5%

(OCTOBER-APRIL 1970-1979)

FIGURE 7





Percentage of periods
October–April 1970–1980

HEATHROW
WIND CHILL (Siple–Passel)
for 30 DEGREE SECTORS

such a rose for Heathrow using 3 Siple-Passel index ranges, namely 900-1099 W/m^2, 1100-1299 W/m^2 and 1300 W/m^2 or more and 12 wind direction sectors. Values are expressed as percentages of time during all the winter months October - April of years 1970-80. For example, for sector 20°-40° the chill index was in the range 900-1099 W/m^2 for 2.5% of the time (1411 hours), in the range 1100-1299 W/m^2 for 0.4% of the time (213 hours) and 1300 W/m^2 or more for 0.03% of the time (17 hours); the corresponding winter averages are 128, 19 and $1^1/_2$ hours respectively. Considering all wind directions, the winter averages for the above 3 index ranges are 1011 hours (42 days), 92 hours (4 days) and 4 hours respectively. Other parts of the country will experience different periods with chilling winds, as illustrated in Figure 4, but it is also important to bear in mind the significant local differences in index brought about by terrain, altitude and topography.

The computer program that analyses wind-chill using the Siple-Passel formula also produces a frequency table of equivalent temperature in 4°C ranges versus wind direction in 30° sectors.

4.3 Energy management

Calculations of accumulated temperature below a nominated base temperature (expressed in terms of 'heating degree days') are widely used for monitoring and predicting the energy consumption for space heating in buildings. They enable allowances for weather variations to be made when comparing the efficiency of plant for one heating season with the efficiency during previous seasons. They can also be used for predicting fuel consumption of heating plant over long periods (Energy Efficiency Office, 1985).

However, fuel consumption is not solely related to temperature. The physical characteristics of the building and the manner in which it is used can also have a significant effect, as can other meteorological factors such as direct and diffuse solar radiation and wind speed. A 'climatic severity index' taking account of this has been proposed following work at the University of Strathclyde (Markus et al, 1984). The sensitivity of space heating energy use to the main climatic parameters was tested using a computer-based thermal model. A simplified parametric study was run to assess the relationship between energy use and climatic severity for 30 different types of house defined in terms of thermal capacity, location, window area, infiltration and insulation.

The use of a modified heating degree day based upon wind-chill equivalent temperature has been proposed by Dare (1981). An average daily equivalent temperature calculated from the Siple-Passel formula was compared with a base temperature of 65°F at various stations in USA during winters 1976/77 and 1977/78. No correlations with energy use were presented, nevertheless this does appear to be a useful method of taking the combined cooling effect of low temperature and wind speed into account when assessing the energy used to heat buildings, particularly those that are not well insulated. Steadman reports that work is currently in progress with the aim of estimating heating (and cooling and dehumidifying) needs in terms of apparent (i.e. equivalent) temperature (Steadman, 1984).

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